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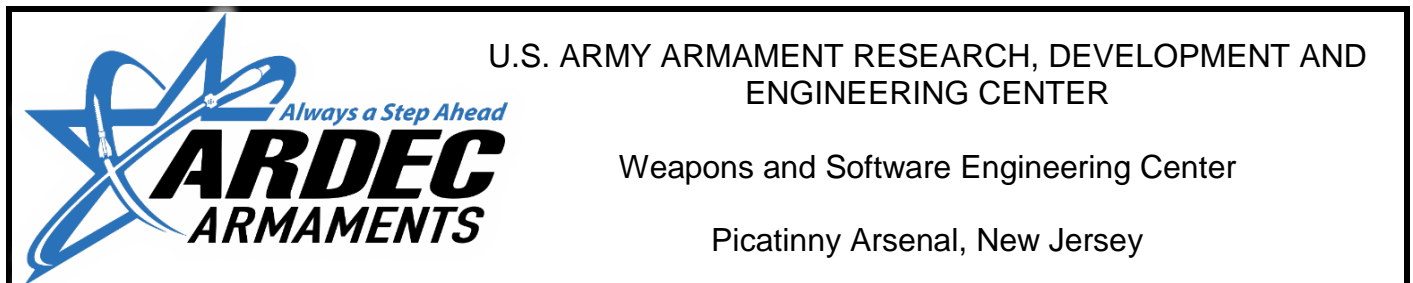
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Technical Report ARWSE-TR-17011

CALCULATION OF WEAPON PLATFORM ATTITUDE AND CANT USING AVAILABLE SENSOR FEEDBACK

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February 2018

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Weapons and Software Engineering Center

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14. ABSTRACT

When firing artillery, there is typically a maximum angle that the platform cannot exceed relative to the Earth plane. This is due to the large recoil forces involved and the risk of destabilizing the platform the weapon is mounted to. Mobile systems are particularly sensitive to this as the attitude of the platform relative to Earth is constantly changing. A simple solution is to add pitch and roll sensors directly to the platform. However, many mobile systems already have an assortment of sensors that can be used to calculate the platform attitude.

This report provides a method to calculate the yaw, pitch, and roll attitude of the weapon platform relative to Earth as well as determine the maximum resulting platform cant and the heading of that cant relative to the platform. These calculations are performed using feedback from sensors providing yaw, pitch, and roll attitude of the gun relative to Earth and azimuth and elevation angles of the gun relative to the platform.

15. SUBJECT TERMS

Artillery Indirect fire Automation Weapon cant Kinematics Euler angles Rotation Transformations

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SUMMARY

This report describes a method to calculate weapon platform attitude relative to Earth as well as determine the maximum resulting platform cant and heading of that cant relative to the weapon platform. These calculations are performed using sensors that may already exist on an indirect weapon system. Calculation of platform cant is an important consideration in operation of large caliber mobile weapons.

INTRODUCTION

U.S. Army weapon systems are designed to be deployed and operated wherever a need arises. This design requirement necessitates operation on a myriad of terrain types. This includes hills, mountains and ravines–locations where level ground is rare or unavailable. It follows that successful development of mobile weapon systems must incorporate operation on sloped terrain.

Sloped terrain presents challenges for firing large caliber weapons. When a weapon is fired, the forward momentum of the discharge is equally reflected to the weapon in the form of a recoiling impulse. That recoiling force can be minimized via a recoil system, which applies a lesser counter force over a calculated distance to spread the impulse over a greater period of time. However, even with sophisticated recoil systems, large caliber guns can impart significant forces into the weapon mount and subsequently the weapon platform. Figure 1 illustrates a large platform cant combined with a low firing angle tangential to that cant. Firing in this configuration could destabilize the platform, possibly resulting in a vehicle rollover.
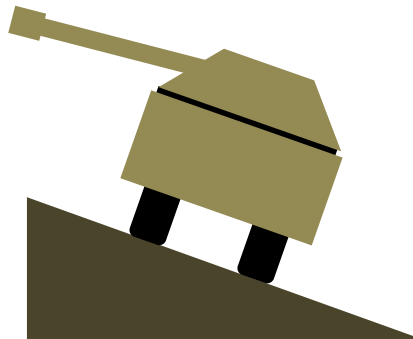

Figure 1
Excessive cant

Sloped terrain can also impact non-firing operations. Traversing on a level platform requires force to accelerate the inertia of the mass and overcome any frictional losses. When canted, a gravitational component is added. That additional load increases with the cant angle and is reflected to the traversing mechanism requiring additional force to overcome. There are also instances when cant must be minimized in order to perform certain maintenance procedures such as boresighting the gun tube.

Due to the challenges presented by operation on uneven terrain, determination of the weapon cant is essential. Computer controlled indirect weapon systems typically have an attitude sensing device that is aligned to the gun tube and enables precise pointing of the weapon. This device provides the attitude of the gun tube relative to Earth using a series of rotations (yaw, pitch, and roll) called Euler angles. In addition, these systems often incorporate sensors to indicate the angles of the traversing and elevating actuators relative to the platform. The remainder of this report

will describe how to use the weapon attitude and actuator sensor data to calculate the attitude of the platform relative to Earth as well as the maximum cant and heading values.

Coordinate Systems

In order to solve kinematic equations, the frames of reference must be defined. This report defines the Earth reference frame (fig. 2) as an orthogonal system with the origin of the frame placed at the weapon's location on the Earth's surface. From the origin, north is the X axis, the Z axis points downward toward the center of the earth sphere, and the Y axis completes the orthogonal reference frame using the right hand rule. Note that north could be true north, magnetic north, grid north, etc., as long as a single definition is applied throughout.
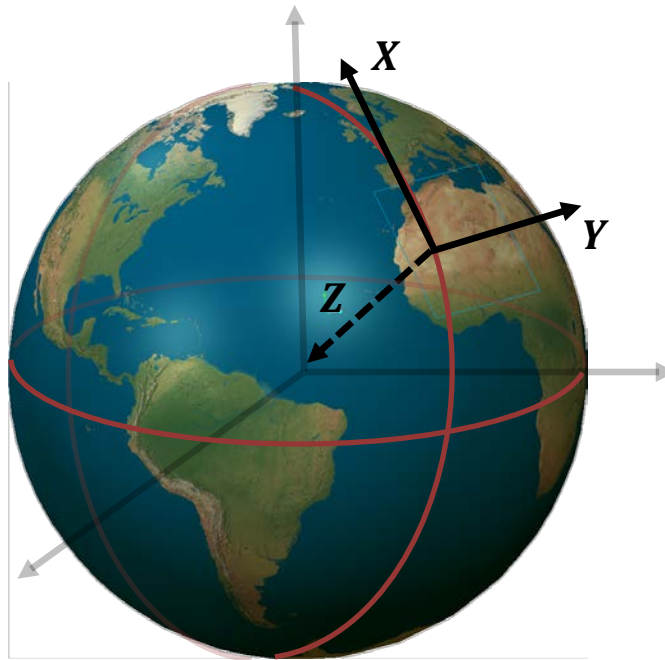

Figure 1
Earth reference frame

Actuators traverse and elevate the gun barrel relative to the system platform. The gun to platform relationship is defined using a reference frame that is different than the Earth reference frame described previously. The origin of the platform reference frame typically exists at or near the intersection of the traverse axis and the elevation axis. For the platform reference frame, the Z axis extends down along the traverse axis of rotation. The X axis extends toward what is established to be the 0 azimuth reference of the platform at an angle normal to the Z axis (typically what would be considered the front of the platform). The Y axis completes the orthogonal reference frame using the right hand rule. An example platform reference frame is illustrated in figure 3.
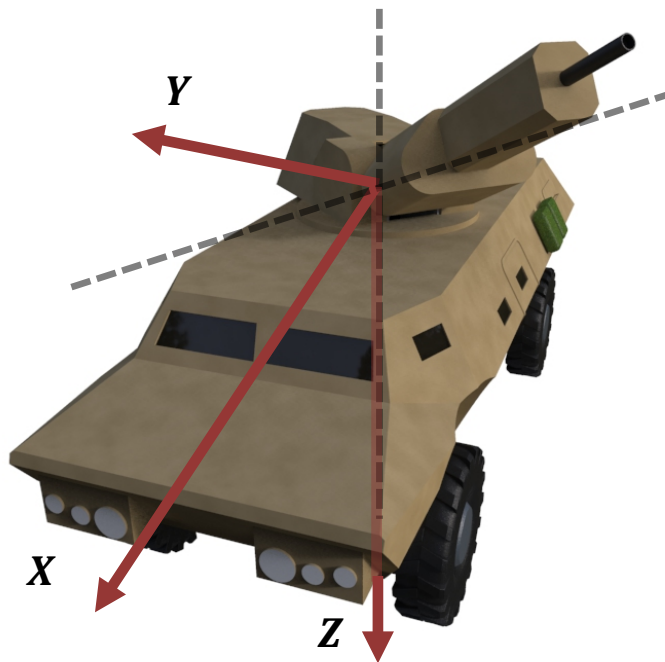
Figure 2
Platform reference frame

When performing rotation transformations between reference frames, an intermediate reference frame is used to perform the operations. This is referred to as the local reference frame. The local reference frame is initially coincident with the starting reference frame. It is subsequently rotated about its axes in the necessary series of motions that conclude with it being coincident with the desired reference frame.

The Problem

Determination of the maximum platform inclination angle relative to Earth (cant) is essential to ensure effective and safe operation of a weapon system. To accomplish this, the pitch and roll angles of the platform must be determined. The pitch and roll angles can then be used to calculate the maximum cant and heading for comparison with vehicle stability limits. The following paragraphs provide equations and methods to calculate those solutions.

METHODS, ASSUMPTIONS, AND PROCEDURES

Conventions and Variable Definitions

Before describing the equations to solve the aforementioned problems, it is important to define the conventions and variables to be used. This report assumes a system that outputs Earth referenced weapon attitude in ZYX Euler angles. Other conventions would require recalculation of the equations.

Table 1 defines the variables used in the provided equations. Subscripts are used to identify the object being measured and/or the reference frame. Angles are represented using radians.

Table 1
Variable definitions

Variable	Definition
X_e, Y_e, Z_e	Axes of Earth reference frame
X_p, Y_p, Z_p	Axes of platform reference frame
X, Y, Z	Axes of the local reference frame
ψ_{Ge}	Gun attitude yaw rotation (Earth reference)
θ_{Ge}	Gun attitude pitch rotation (Earth reference)
φ_{Ge}	Gun attitude roll rotation (Earth reference)
ψ_{Gp}	Gun attitude yaw rotation (Platform reference)
θ_{Gp}	Gun attitude pitch rotation (Platform reference)
ψ_{Pe}	Platform attitude yaw rotation (Earth reference)
θ_{Pe}	Platform attitude pitch rotation (Earth reference)
φ_{Pe}	Platform attitude roll rotation (Earth reference)
C_{Pe}	Platform maximum cant angle (Earth reference)
H_{Cp}	Platform maximum cant angle yaw (Platform reference)

       This report assumes the reader is familiar with coordinate systems, rotation matrices, Euler angles, etc. For convenience, the three basic rotation matrices are provided below. The subscripts indicate the axis upon which the rotation is being applied. Positive rotation is defined as clockwise when viewed from the origin outwards. Additional information regarding the aforementioned subjects can be found in reference 1.

$$R_Z(\psi) = \begin{bmatrix} cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(1)

$$R_Y(\theta) = \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix}$$

(2)

$$R_X(\varphi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\varphi & -sin\varphi \\ 0 & sin\varphi & cos\varphi \end{bmatrix}$$

(3)

Transformation from the Earth Referenced Frame to the Platform Reference Frame

In order to generate a rotation matrix relating the platform reference frame to the Earth reference frame, one must perform a series of five rotations via the basic rotation matrices. These rotations describe the rotations required to align the Earth reference frame with the platform reference frame.

$$R_{EV} = R_Z(\psi_{Ge})R_Y(\theta_{Ge})R_X(\varphi_{Ge})R_Y(-\theta_{Gp})R_Z(-\psi_{Gp}) \tag{4}$$

The transformation begins with the local reference frame coincident with the Earth reference frame. The yaw, pitch, and roll angles provided by the gun attitude sensor are sequentially applied to rotations about the Z, Y, and X axes respectively. Once those rotations have been performed, the local reference frame is aligned with the gun tube (the X axis is coincident with the centerline of the gun tube). At this point, a negative rotation about the Y axis is applied using the elevation actuator angle. This rotation aligns the local reference frame's XY plane with the platform reference frame's X_PY_P plane. Finally, a negative rotation about the Z axis using the traverse actuator angle fully aligns the local reference frame with the platform reference frame.

Substituting the basic rotation matrices into the five rotations yields equation 5. Note that the sine and cosine functions are represented using s and c respectively to minimize the text required.

$$R_{EV} = \begin{bmatrix} c\psi_{Ge} & -s\psi_{Ge} & 0 \\ s\psi_{Ge} & c\psi_{Ge} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\theta_{Ge} & 0 & s\theta_{Ge} \\ 0 & 1 & 0 \\ -s\theta_{Ge} & 0 & c\theta_{Ge} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\varphi_{Ge} & -s\varphi_{Ge} \\ 0 & s\varphi_{Ge} & c\varphi_{Ge} \end{bmatrix} \begin{bmatrix} -c\theta_{Gp} & 0 & -s\theta_{Gp} \\ 0 & 1 & 0 \\ s\theta_{Gp} & 0 & -c\theta_{Gp} \end{bmatrix} \begin{bmatrix} -c\psi_{Gp} & s\psi_{Gp} & 0 \\ -s\psi_{Gp} & -c\psi_{Gp} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5}$$

Performing the matrix multiplication and solving using the values provided by the gun attitude and actuator sensors results in a 3x3 matrix of values ranging from 0 to 1. The columns represent the three unit vectors that form the Cartesian coordinates of the local reference frame (aligned with platform reference frame) with respect to the Earth reference frame. Equation 6 present this with i, j, and k representing the unit vectors of the X, Y, and Z axes. The Cartesian coordinates of each unit vector are represented by the x, y, and z subscripts.

$$i = \begin{bmatrix} Xx \\ Xy \\ Xz \end{bmatrix} j = \begin{bmatrix} Yx \\ Yy \\ Yz \end{bmatrix} k = \begin{bmatrix} Zx \\ Zy \\ Zz \end{bmatrix} \tag{6}$$

Conversion of Rotation Matrix to ZYX Euler Angles

The ZYX Euler angles can be calculated from a given rotation matrix using equations 7 through 10. The inverse kinematic calculations that produced these equations can be found in reference 2.

Given a rotation matrix represented as:

$$R = \begin{bmatrix} M_{Xx} & M_{Yx} & M_{Zx} \\ M_{Xy} & M_{Yy} & M_{Zy} \\ M_{Xz} & M_{Yz} & M_{Zz} \end{bmatrix} \tag{7}$$

$$\psi = \text{atan2}\left(\frac{M_{Xy}}{M_{Xx}}\right) \tag{8}$$

$$\theta = \text{atan2}\left(\frac{-M_{Xz}}{M_{Xx}\cos(\psi) + M_{Xy}\sin(\psi)}\right) \tag{9}$$

$$\varphi = \text{atan2}\left(\frac{M_{Zx}\sin(\psi) - M_{Zy}\cos(\psi)}{M_{Yy}\cos(\psi) - M_{Yx}\sin(\psi)}\right) \tag{10}$$

Note that atan2 is a programming function that uses the input values to determine the correct quadrant returned from an arctangent operation.

For the unusual case where the platform is pointing straight up or straight down, the angles are as follows:

$$\text{if } ((M_{Xx} == 0) \text{ \&\& } (M_{Xy} == 0)): \quad \psi = 0, \quad \theta = \frac{\pi}{2}, \quad \varphi = \text{atan2}\left(\frac{M_{Yx}}{M_{Yy}}\right) \tag{11}$$

Calculation of Maximum Platform Cant and Heading

Two intersecting planes create an angle between them. Of equal magnitude is the angle formed between vectors projecting normally from their respective planes and originating at a point along the line of intersection. This is shown in figure 4 with the angle θ_v between vectors n_1 and n_2 being equal to the angle θ_p formed between the two planes.
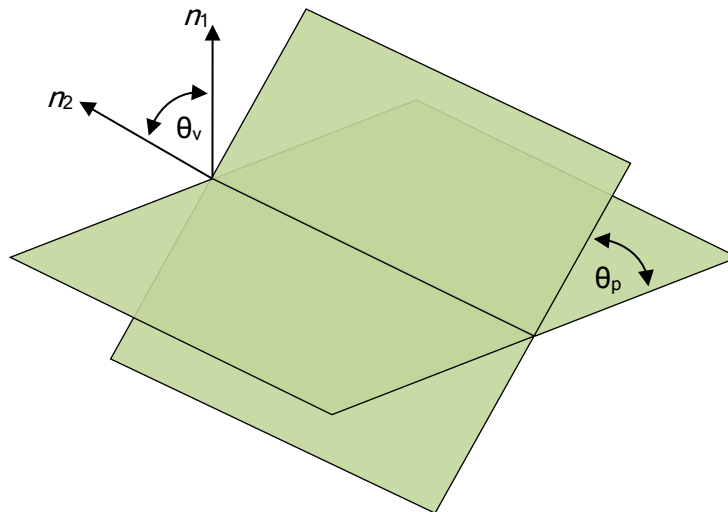

Figure 3
Intersecting planes

The angle between two vectors is equal to the arc cosine of the dot product of the vectors divided by the product of their magnitudes.

$$\theta = acos\left(\frac{n_1 \cdot n_2}{\|n_1\|\|n_2\|}\right) \tag{12}$$

The maximum cant of a platform relative to Earth is represented by the angle between the Earth reference frame's Z axis and the Z axis of the platform reference frame. To determine this angle, a unit vector representing the platform reference frame's Z axis must be transformed into the Earth reference frame. Since the cant direction sought is referenced to the platform reference frame rather than the Earth reference frame, the rotation matrix omits the traverse rotation about the Z axis.

$$R = R_Y(\theta_{Pe})R_X(\varphi_{Pe}) \tag{13}$$

$$R = \begin{bmatrix} cos\theta_{Pe} & 0 & sin\theta_{Pe} \\ 0 & 1 & 0 \\ -sin\theta_{Pe} & 0 & cos\theta_{Pe} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\varphi_{Pe} & -sin\varphi_{Pe} \\ 0 & sin\varphi_{Pe} & cos\varphi_{Pe} \end{bmatrix} = \begin{bmatrix} cos\theta_{Pe} & sin\theta_{Pe}sin\varphi_{Pe} & sin\theta_{Pe}cos\varphi_{Pe} \\ 0 & cos\varphi_{Pe} & -sin\varphi_{Pe} \\ -sin\theta_{Pe} & cos\theta_{Pe}sin\varphi_{Pe} & cos\theta_{Pe}cos\varphi_{Pe} \end{bmatrix} \tag{14}$$

The transformed Z axis unit vector is the product of the rotation matrix and the Z unit vector:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} sin\theta_{Pe}cos\varphi_{Pe} \\ -sin\varphi_{Pe} \\ cos\theta_{Pe}cos\varphi_{Pe} \end{bmatrix} \tag{15}$$

The maximum cant angle is solved using equation 12. In this case, n_1 is Earth's Z axis unit vector and n_2 is the platform's transformed Z axis unit vector. Since the vectors represent unit vectors of length 1, the equation simplifies to:

$$C_{Pe} = acos\left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \cdot \begin{bmatrix} sin\theta_{Pe}cos\varphi_{Pe} \\ -sin\varphi_{Pe} \\ cos\theta_{Pe}cos\varphi_{Pe} \end{bmatrix}\right) = acos(cos\theta_{Pe}cos\varphi_{Pe}) \tag{16}$$

The traverse angle of the maximum cant relative to the platform's heading is found using equation 8.

$$H_{Cp} = atan2\left(\frac{y}{x}\right) = atan2\left(\frac{-sin\varphi_{Pe}}{sin\theta_{Pe}cos\varphi_{Pe}}\right) \tag{17}$$

Example

In this example, the gun attitude and actuator sensors are outputting the angles shown in table 2. The steps required to convert those angles to platform attitude and cant angles follow. This example represents angles using North Atlantic Treaty Organization (NATO) angular mils of which there are 6,400 in a circle.

Table 2
Example data

Data	Variable	Value
Gun attitude yaw rotation (Earth reference)	ψ_{Ge}	4,712 mils
Gun attitude pitch rotation (Earth reference)	θ_{Ge}	645 mils
Gun attitude roll rotation (Earth reference)	φ_{Ge}	-12 mils
Gun attitude yaw rotation (Platform reference)	ψ_{Gp}	350 mils
Gun attitude pitch rotation (Platform reference)	θ_{Gp}	100 mils

The first step is to convert the units from mils to radians. Conversion in both directions is shown in equations 18 and 19.

.

$$X_r = 2\pi \left(\frac{X_m}{6400} \right) \tag{18}$$

$$X_m = 6400 \left(\frac{X_r}{2\pi} \right) \tag{19}$$

The resulting values are:

$$\psi_{Ge} = 4.626 \, rad$$
$$\theta_{Ge} = 0.633 \, rad$$
$$\varphi_{Ge} = -0.012 \, rad$$
$$\psi_{Gp} = 0.344 \, rad$$
$$\theta_{Gp} = 0.098 \, rad$$

The next step is to generate the rotation transformation matrix.

$$R = R_Z(4.626)R_Y(0.633\,)R_X(-0.012)R_Y(-0.344)R_Z(-0.098) \tag{20}$$

The resulting matrix equals:

$$R = \begin{bmatrix} -0.4046 & 0.9139 & -0.0323 \\ -0.7803 & -0.3635 & -0.5090 \\ -0.4769 & -0.1807 & 0.8602 \end{bmatrix} \tag{21}$$

Application of conversion equations 8 through 10 yields:

$$\psi_{Pe} = \operatorname{atan}2 \left(\frac{-0.7803}{-0.4046} \right) = -2.049 \, rad = 6400 \left(\frac{-2.049}{2\pi} \right) = -2087 \, mils = 4313 \, mils \tag{22}$$

$$\theta_{Pe} = \operatorname{atan}2\left(\frac{0.4769}{-0.4046\cos(\psi_{Pe}) - 0.7803\sin(\psi_{Pe})}\right) = \operatorname{atan}2\left(\frac{0.477}{.879}\right) = .497\ rad = 506\ mils \qquad (23)$$

$$\varphi_{Pe} = \operatorname{atan}2\left(\frac{-0.0323\sin(\psi_{Pe}) + 0.5090\cos(\psi_{Pe})}{-0.3635\cos(\psi_{Pe}) - 0.9139\sin(\psi_{Pe})}\right) = -0.207\ rad = -211\ mils \qquad (24)$$

With the yaw, pitch and roll angles of the platform relative to Earth determined, the cant and cant heading can be determined using equations 16 and 17.

$$C_{Pe} = \operatorname{acos}\big(cos(.497)cos(-0.207)\big) = .535\ rad = 545\ mils \qquad (25)$$

$$H_{Cp} = \operatorname{atan}2\left(\frac{-sin(-0.207)}{sin(.497)cos(-0.207)}\right) = 0.415\ rad = 423\ mils \qquad (26)$$

RESULTS AND DISCUSSIONS

The equations and methods presented in this report have been used successfully on multiple systems. Those systems used an Inertial Navigation Unit to provide the gun to Earth Euler angles and absolute encoders to provide the gun to platform azimuth and elevation angles. The weapon system software calculated the platform attitude at a periodic interval, providing active monitoring of the platform attitude. That information allowed the system to prevent excessive loads on the traversing actuator and prohibit firing at conditions that were outside safe limits. The availability of the data in real time to the user allows for positioning of the platform (vehicle) in an acceptable orientation for operations.

There are some drawbacks to deriving these values rather than measuring them directly with dedicated sensors. Since the values are computed rather than directly measured, their accuracy is a function of the five input sensors and the round off errors accumulated from the multiple calculations. The amount of error allowed can be controlled by implementing appropriately rated sensors and performing calculations using functions of an adequate precision (i.e., use double precision floating types). Another drawback is the additional load on the computing system. There are several floating point operations required that could be "expensive" on less capable processors.

While accuracy and processor load are detractors to this method, they can be accounted for. There is significant savings in cost, weight, and power consumption realized by eliminating the need for additional sensor units and cabling. The provided equations are easily implemented in software. MATLAB code has been provided in the appendix to demonstrate the algorithms. In addition, c code is available from the author upon request.

CONCLUSIONS

Through the use of rotation transformations and trigonometric functions, solutions were found for the aforementioned problem. These calculations allow the user to determine platform attitude and maximum cant relative to Earth without the need for additional sensors.

REFERENCES

1. Stapp, Joshua, "Kinematics of Laying an Automated Weapon System," Technical Report ARWSE-TR-16024, U.S. Army ARDEC, Picatinny Arsenal, NJ, 2017.

2. Snyder, Wesley E., "Industrial Robots: Computer Interfacing and Control," Englewood Cliffs, NJ: Prentice-Hall, pp. 133-137, 1985.

APPENDIX
MATLAB CODE

MATLAB Source Code

```
function CantCalc

clear
format bank
GunE = struct('Yaw', 0, 'Pitch', 0, 'Roll', 0);
PlatformE = struct('Yaw', 0, 'Pitch', 0, 'Roll', 0, 'Cant', 0, 'Heading', 0);
Check = struct('Yaw', 0, 'Pitch', 0, 'Roll', 0);
GunP = struct('Az', 0, 'El', 0);
running = 1;
M=[0,0,0;
   0,0,0;
   0,0,0];

while (running == 1),
    clc
    %Print current data to screen
    fprintf(' _____\n');
    fprintf('|                 Platform Angles Calculation                   |\n');
    fprintf('|---------------------------------------------------------------|\n');
    fprintf('|      Gun(E)     |    Gun(P)    |      Platform    |   Verify   |\n');
    fprintf('|---------------------------------------------------------------|\n');
    fprintf('| Yaw     %7.3f | Az  %7.3f | Yaw      %7.3f | Yaw     %7.3f |\n', ...
              GunE.Yaw, GunP.Az,  PlatformE.Yaw, Check.Yaw);
    fprintf('| Pitch   %7.3f | El  %7.3f | Pitch    %7.3f | Pitch   %7.3f |\n', ...
              GunE.Pitch, GunP.El, PlatformE.Pitch, Check.Pitch);
    fprintf('| Roll    %7.3f |              | Roll      %7.3f | Roll    %7.3f |\n', ...
              GunE.Roll,              PlatformE.Roll, Check.Roll);
    fprintf('|                 |              | Cant      %7.3f |            |\n', ...
                                      PlatformE.Cant);
    fprintf('|                 |              | Heading %7.3f |            |\n', ...
                                      PlatformE.Heading);
    fprintf('|_____|_____|_____|_____|\n\n');

    %Print menu to screen and get command
    fprintf('*** Command Menu ***\n');
    fprintf('1) Enter New Gun-Earth Attitude (rads)\n');
    fprintf('2) Enter New Gun-Platform Angles (rads)\n');
    fprintf('3) Quit Program\n\n');

    mode = input('Enter Command: ');

    switch (mode)
        case 1
            %Get Gun Attitde from user (relative to earth)
            GunE.Yaw=input('Enter Yaw (rads): ');
            GunE.Pitch=input('Enter Pitch (rads): ');
            GunE.Roll=input('Enter Roll (rads): ');
        case 2
            %Get Gun Orientation from user (relative to platform)
            GunP.Az=input('Enter Azimuth (rads): ');
            GunP.El=input('Enter Elevation (rads): ');
        case 3
            running = 0;
            break;
        otherwise
            disp('Invalid Command');
            break;
    end

    %Create Transformation Matrix
    M=aboutz(GunE.Yaw);
    M=M*abouty(GunE.Pitch);
    M=M*aboutx(GunE.Roll);
    M=M*abouty(-GunP.El);
    M=M*aboutz(-GunP.Az);
```

```matlab
    %Generate ypr angles
    [PlatformE.Yaw,PlatformE.Pitch,PlatformE.Roll]=RtoYPR(M);

    %Generate Cant and Heading
    PlatformE.Cant = acos(cos(PlatformE.Pitch) * cos(PlatformE.Roll));
    PlatformE.Heading = atan2(-sin(PlatformE.Roll), ...
            sin(PlatformE.Pitch * cos(PlatformE.Roll)));

    %Create new transformation Matrix using platform angles
    M=aboutz(PlatformE.Yaw);
    M=M*abouty(PlatformE.Pitch);
    M=M*aboutx(PlatformE.Roll);
    M=M*aboutz(GunP.Az);
    M=M*abouty(GunP.El);

    %Generate ypr angles of new rotation transformation using platform values
    [Check.Yaw,Check.Pitch,Check.Roll]=RtoYPR(M);
end

%Helper functions
function [M]=aboutx(a)
M=[1,0,0;
   0,cos(a),-sin(a);
   0,sin(a),cos(a)];

function [M]=abouty(a)
M=[cos(a),0,sin(a);
   0,1,0;
   -sin(a),0,cos(a)];

function [M]=aboutz(a)
M=[cos(a),-sin(a),0;
   sin(a),cos(a),0;
   0,0,1];

function [y,p,r]=RtoYPR(M)
if M(2,1) == 0 && M(1,1) == 0  % Pointing straight up or down.
    y = 0;
    p = pi;
    r = atan2(M(1,2),M(2,2));
else
    y = atan2(M(2,1),M(1,1));
    cyaw = cos(y);
    syaw = sin(y);
    p = atan2(-M(3,1),M(1,1)*cyaw + M(2,1)*syaw);
    r = atan2(M(1,3)*syaw - M(2,3)*cyaw,M(2,2)*cyaw - M(1,2)*syaw);
    if (y < 0)
        y = y + (2 * pi);
    end
end
```

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REVIEW AND APPROVAL OF ARDEC TECHNICAL REPORTS

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and Cant Using Available Sensor Feedback
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Jose Santiago

14 FEB 2017

Division Chief   (Date)

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Jose Santiago   2/21/18

Division Chief   (Date)

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